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AD-A278 628



**Propellant Stress Relief Groove
for the Titan IV SRMU**

November 1993

Prepared by

**I-SHIH CHANG
Engineering and Technology Group**

Prepared for

**SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE MATERIEL COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245**



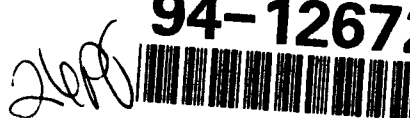
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This final report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-88-C-0089 with the Space and Missile Systems Center, P. O. Box 92960, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by J. D. Gilchrist, General Manager, Vehicle and Control Systems Division, Engineering and Technology Group, and J. F. Willacker, General Manager, Titan Launch Systems, Space Launch Operations, Programs Group. The project officer is Lt. Col. D. Van Mullem.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER

Douglas A. Van Mullem

REPORT DOCUMENTATION PAGE

Form Approved

OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 1993		3. REPORT TYPE AND DATES COVERED TR/Jan. 1991 to Jan. 1993	
4. TITLE AND SUBTITLE Propellant Stress Relief Groove for the Titan IV SRMU				5. FUNDING NUMBERS	
6. AUTHOR(S) I-Shih Chang					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Aerospace Corporation 2350 E. El Segundo Blvd. El Segundo, CA 90245-4691				8. PERFORMING ORGANIZATION REPORT NUMBER TR-93(3530)-2	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Space and Missile Systems Center Air Force Materiel Command 2430 E. El Segundo Blvd. Los Angeles Air Force Base, CA 90245				10. SPONSORING/MONITORING AGENCY REPORT NUMBER SMC-TR-94-24	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A method has been developed to design a propellant stress relief groove (SRG) for solid rocket motors. The method considers a time-dependent pressure distribution in both burn-back and "burn-forward" analyses and allows a desired bondline stress condition to be incorporated into the SRG design. Application of the method to obtain an improved propellant SRG for the Titan IV Solid Rocket Motor Upgrade (SRMU) is illustrated in this report. The improved propellant SRG obtained from this method for the Titan IV SRMU provides significant enhancement in the propellant structural margin of safety throughout motor firing. <div style="text-align: right;">DISCONTINUED 3</div>					
14. SUBJECT TERMS Titan IV Solid Rocket Motor, Propellant, Stress Analysis				15. NUMBER OF PAGES 28	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited		

PREFACE

The author wishes to thank Mr. N. N. Au for his guidance and leadership during this SRMU stress relief groove design project; Drs. Y. S. Pan, N. R. Patel, S. N. Sallam, and S. H. Yang for providing the results of the structural margin of safety calculation; and Mr. J. Vana, Mr. M. Tam, Maj. A. Saenz, and Maj. W. Hurley for valuable comments.

Accession For	
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Unannounced	<input type="checkbox"/>
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NOMENCLATURE

a	=	constant in propellant burn-rate equation
β	=	intersection angle between propellant and bondline ($^{\circ}$)
H	=	detachment height of the propellant stress relief groove in Figure 8 (in.)
L	=	depth of the propellant stress relief groove in Figure 8 (in.)
n	=	pressure exponent in propellant burn-rate equation
P	=	pressure (psia)
R	=	radial coordinate from motor centerline (in.)
r	=	propellant burn-rate (in./sec)
X	=	axial coordinate for the SRG analysis (in.)
x	=	axial coordinate for the pressure distribution (in.)

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1. INTRODUCTION

The U. S. Air Force Titan IV Solid Rocket Motor Upgrade (SRMU)¹, shown in Figure 1, is being developed to launch large payloads. This is a 3.20-m (126-in.) diameter, 34.26-m (112.4-ft) long, three-segment motor with a graphite epoxy composite case. The motor is loaded with 312,460 kg (688,850 lb) of hydroxyl-terminated polybutadiene (HTPB) propellant and weighs about 350,517 kg (772,750 lb). The nozzle throat is made of graphite/phenolic. The forward and aft exit cone insulators are made of tape-wrapped carbon/phenolic. The nozzle is supported by a flexseal assembly with a maximum 6° gimbals capability. The maximum mass flow rate is 2585.50 kg (5700 lb/sec) which produces approximately 7.117 million Newton (1.6 million lbf) thrust for each SRMU during liftoff. The Titan IV with two SRMUs is designed to provide a 25% increase in payload delivery capability from the current Titan IV with the steel-case motors. The Titan IV SRMU will be the most powerful solid rocket motor in the U. S. Air Force space launch vehicle program.

In order to avoid an excessive stress concentration at the bondline between the propellant and the motor case insulation during motor processing, storage, and motor firing, a propellant stress relief groove is molded into the forward and aft faces of the propellant grain in the center segment and into the forward face of the propellant grain in the aft segment of the SRMU (see Figure 1). For a giant motor like the SRMU, incorporation of a robust stress relief groove (SRG) in the grain during the motor qualification stage is of paramount importance. This report discusses a novel analysis method that will generate an improved SRG design for the SRMU. The method considers an unconventional "burn-forward" in time from a desired burn-back configuration which will aid in determining the initial SRG shape for the required burn-back configurations. The method is equally applicable to other motors with an SRG molded in the grain of a different configuration from that of the SRMU. Furthermore, the method can be extended to the entire grain design to achieve a predefined, unique ballistic feature for a solid rocket motor.

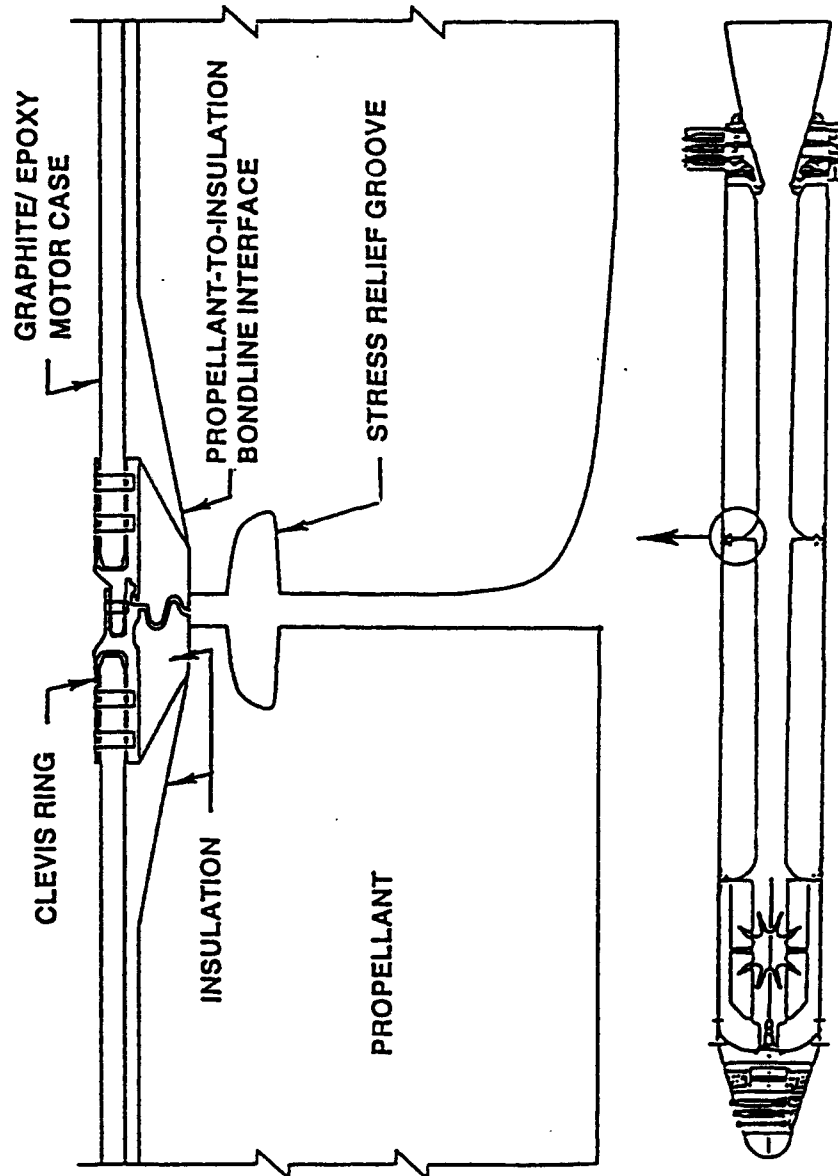


Figure 1. Titan IV SRMU Motor Assembly

2. METHOD OF ANALYSIS

The basic reason for using the stress relief groove in the solid propellant is to alleviate the stress concentration at the bondline between the propellant and the motor case insulation. Making an SRG in the grain, however, will directly affect the propellant stress distribution. From a grain structural analysis viewpoint, an optimized SRG design requires that the strength degradation in the grain and the stress concentration at the bondline be minimized throughout motor firing. Depending on the grain and the insulation configuration, each solid rocket motor has its own specific characteristics and, hence, a unique SRG configuration.

A prerequisite for an accurate grain structural analysis is the knowledge of pressure distribution on the regressing surface of the grain during motor firing. This information can be obtained, for example, from Reference 2, which provides a full Navier-Stokes solution inside motors of an arbitrary configuration. Based on a time-dependent pressure distribution, the burn-back configurations at several time slices during motor firing can be constructed from Reference 2 as a byproduct of the flow field solution or from a well-known, standard method for the grain design given in Reference 3. From these propellant burn-back configurations, the intersection angles at the bondline between the propellant and the motor case insulation can be determined. These intersection angles affect the stress condition at the bondline. A singular-point behavior may occur at large intersection angles at the bondline, which cannot be analyzed structurally and needs to be avoided. Adjusting the intersection angles has the same effect as changing the stress condition at the bondline at any particular time during motor firing. A desired SRG design requires that the stress condition at the bondline not exceed a critical value not only during motor ignition but also throughout motor firing. This can be accomplished by ensuring that the propellant burn-back configurations follow a predetermined pattern during motor firing.

A "burn-forward" analysis is applied here to adjust the burn-back configurations of the grain to a predetermined pattern, which provides the desired bondline stress condition throughout motor firing. Starting with any burn-back configuration, one can reconstruct the corresponding initial grain shape by applying the propellant burn-rate artificially in the opposite direction from that of the normal propellant regression. This is called a "burn-forward" analysis in this study to differentiate it from the usual burn-back analysis in the standard grain design of Reference 3. In the "burn-forward" analysis, the burn-rate also is a function of pressure; but it follows a reversed relationship of the pressure variation with time. For each modified burn-back configuration with a selected intersection angle (stress condition) at the bondline, a "burn-forward" analysis is performed to obtain a unique, initial SRG shape. There will be an initial SRG shape corresponding

to each "burn-forward" analysis at a particular time slice. Enveloping these initial SRG shapes will result in a portion of an SRG configuration, which will produce the desired bondline stress condition throughout motor firing. The remainder of the SRG configuration will be determined by the propellant stress consideration.

The procedures for designing an SRG can be listed as follows:

- a. Perform a standard burn-back analysis based on a time-dependent pressure distribution for a grain with a candidate SRG design.
- b. Modify the propellant burn-back configurations to obtain the selected intersection angles (stress condition) at the bondline throughout motor firing.
- c. Perform a "burn-forward" analysis with a reversed relationship of the pressure variation with time at several time slices to obtain several initial SRG shapes.
- d. Envelope these initial SRG shapes to obtain a portion of an SRG configuration.
- e. Adjust the depth and the detachment height of the SRG to obtain an adequate margin of safety at the bondline and in the SRG during motor ignition.

If necessary, the procedures listed above can be repeated to ensure that the intersection angles at the bondline do not exceed a critical value at any time during motor firing, and the final SRG has the desired structural margin of safety. An example of applying this method to improve the structural margin of safety for an SRG design of the Titan IV SRMU is given in Section 3.

3. APPLICATION TO TITAN IV SRMU

A robust SRG design is required for the Titan IV SRMU to ensure that the grain and the bondline have an adequate margin of safety and are insensitive to the change in physical properties affected by the environment over long-term storage and under a worst case, high-temperature firing condition. The propellant burn-rate, r , is a function of the motor internal pressure, and the motor internal pressure is, in turn, a function of time. For the SRMU, $r = aP^n$, where $a = 0.0677$, $n = 0.2320$, and P is the local pressure on the grain surface.

A solid rocket motor often has severe stress environment at the bondline between propellant and insulation during cooldown and during motor storage at low temperature. For the Titan IV SRMU with the stress relief groove in the propellant, grain structural analyses have been performed (Ref. 1) for the initial grain temperatures of 4.44, 15.56, and 32.22°C (40, 60, and 90°F). During motor operation, the minimum margin of safety occurs in the stress relief groove at 32.22°C (90°F) initial grain temperature. At ignition the chamber pressure rise rate is higher, the propellant strain is higher, and the propellant modulus is lower at high temperatures than at low temperatures. The effects of higher temperature are higher chamber pressure rise rate at ignition, higher propellant strain, and lower propellant modulus during motor firing.

For the motor head-end pressure given in Figure 2, which was obtained from Reference 3 under a high-temperature 32.22°C (90°F) firing condition, the pressure distributions on the deformed grain surface at 11 time slices up to 50 sec after motor ignition have been calculated using the method discussed in Reference 2. The pressure distribution at any other time slice before 50 sec can be obtained by interpolation. Figure 3 illustrates the pressure distribution versus motor length at four different time slices, namely, 1, 5, 10, and 20 sec after motor ignition. The time-dependent pressure is utilized in the standard burn-back analysis for constructing the propellant burn-back configurations and in the "burn-forward" analysis for deriving the initial SRG shapes.

Figure 4 shows the burn-back configurations at several time slices for the preliminary SRG design. After approximately 8 sec into motor firing, the burn-back configuration will intersect the motor case insulation at a location where a rapid change in the slope of the motor case insulation profile occurs. This change in the slope of the motor case insulation profile directly affects the intersection angle at the bondline between the propellant and the motor case insulation and has a bearing on the stress condition at the bondline. The method discussed in Section 2 modifies the intersection angle at the bondline and performs the "burn-forward" analysis at several time slices after 8 sec into motor firing.

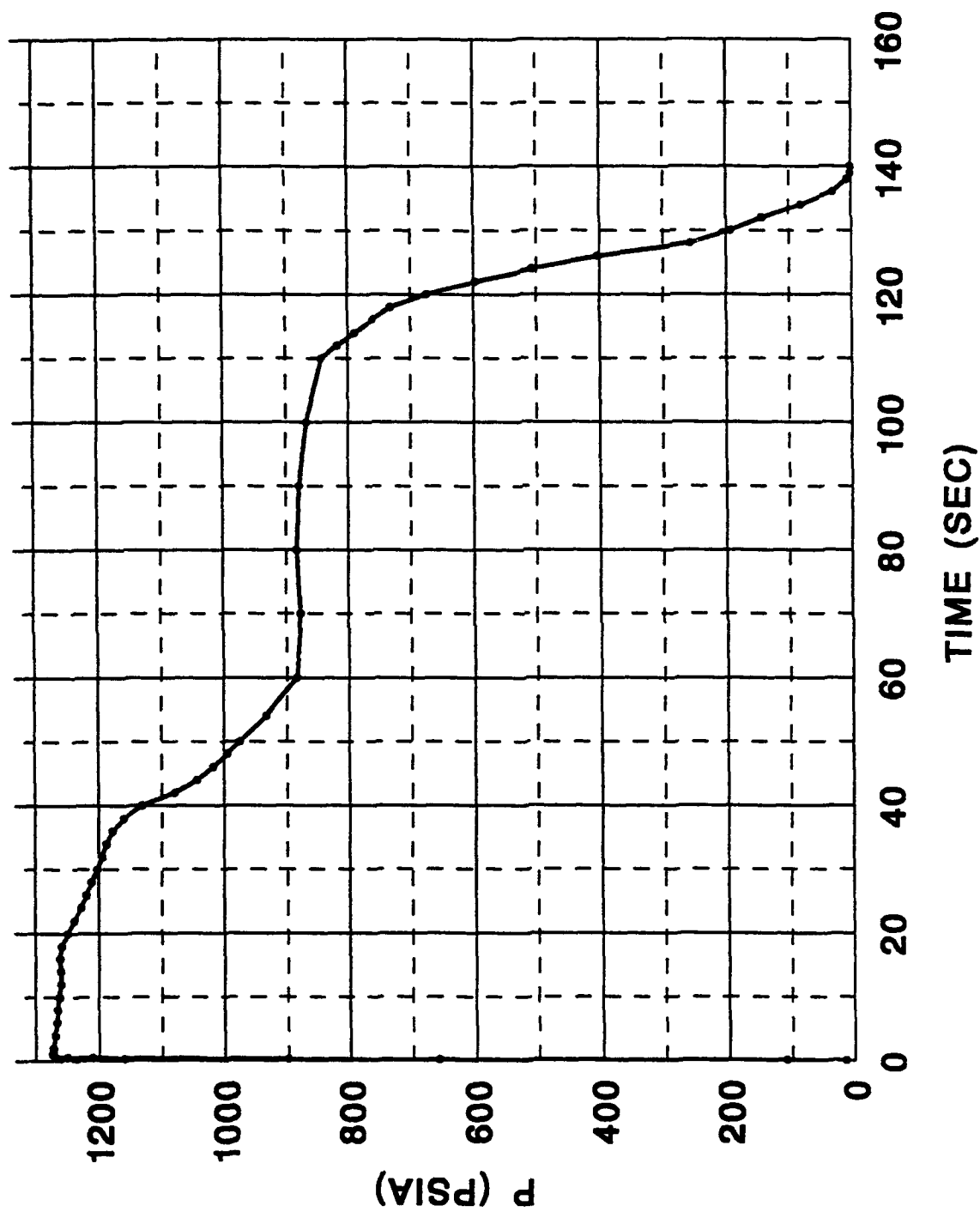


Figure 2. SRMU Head-End Pressure History (90°F)

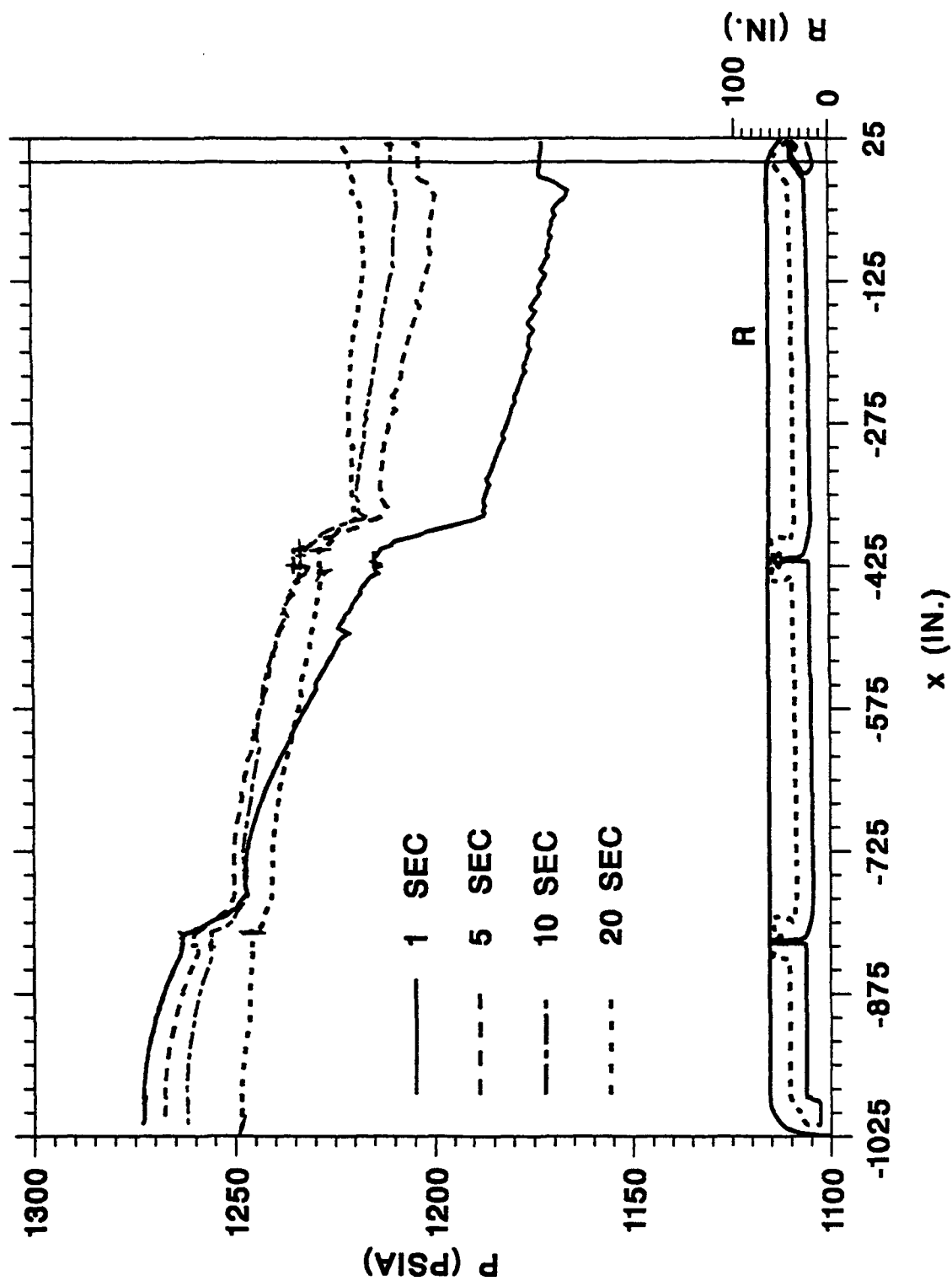


Figure 3. SRMU Pressure Distribution (90°F)

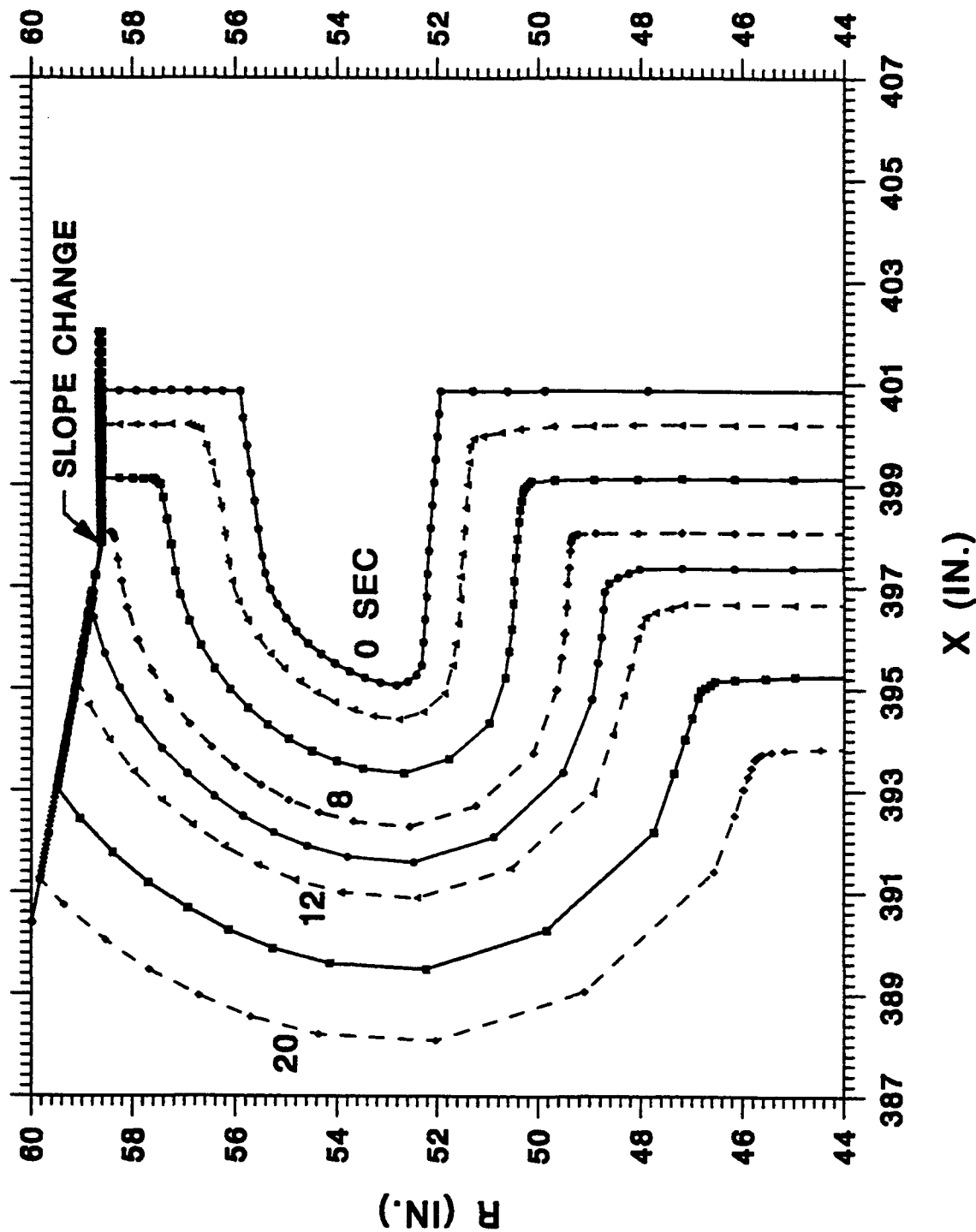


Figure 4. SRMU Preliminary Propellant SRG and Burn-Back
(configurations at 0, 2, 5, 8, 10, 12, 16, and 20 sec)

Figures 5, 6, and 7 illustrate the results of the "burn-forward" analysis from 10, 16, and 20 sec, respectively. The initial SRG shapes obtained from these "burn-forward" analyses are grouped together in Figure 8. Enveloping these initial SRG shapes will produce an upper portion (larger radial coordinate from the motor centerline) of the improved SRG configuration, whose angles (stress condition) at the bondline are less than a critical value at all times during motor firing. For the SRMU, this critical value is set at 45° for a Poisson's ratio = 0.5 and is considered by the structural analysts (Refs. 4 and 5) to be the maximum allowable intersection angle at the bondline between 8 and 20 sec after motor ignition, at which time the propellant burn-back configuration progresses beyond the location of change in the slope of the motor case insulation profile. A singular-point behavior is presumed to exist by some structural analysts, if the intersection angle is greater than this critical value after 8 sec into motor firing. At 20 sec into motor firing, the grain regresses far enough, and the internal pressure of the motor starts a sharp decline as shown in Figure 2. After that time, the structural margin of safety at the bondline or in the groove for the SRMU has increased.

It is necessary to ensure that modification of the propellant burn-back configuration to include the selected intersection angle (desired stress condition) at the bondline does not introduce any local stress concentration in other areas of the burn-back configuration. Thus, in addition to the 45° criterion at the bondline, a smooth profile for the modified propellant burn-back configuration is required.

The lower portion (smaller radial coordinate from motor centerline) of the improved SRG design is adjusted to have a shallower depth, L , than that of the preliminary SRG for an improved propellant strength during motor ignition. The detachment height, H , for the improved SRG shown in Figure 8 reduces to zero when the propellant regression surface reaches the location where a rapid change in the slope of the motor case insulation profile occurs. This can be seen from the final burn-back configurations for the improved SRG design given in Figure 9.

Figure 10 shows a comparison of the preliminary SRG configuration with the improved SRG configuration for the SRMU. Table 1 lists the intersection angles at the bondline after 8 sec into motor firing. It shows that the improved SRG has a smaller intersection angle and less bondline stress concentration than that of the preliminary SRG. Before 8 sec, both the preliminary and the improved SRGs have the same vertical intersection angle at the bondline. But the improved SRG, by virtue of its shallow depth and a smooth, gradual change in the slope, also provides a better structural strength during motor ignition than that of the preliminary SRG.

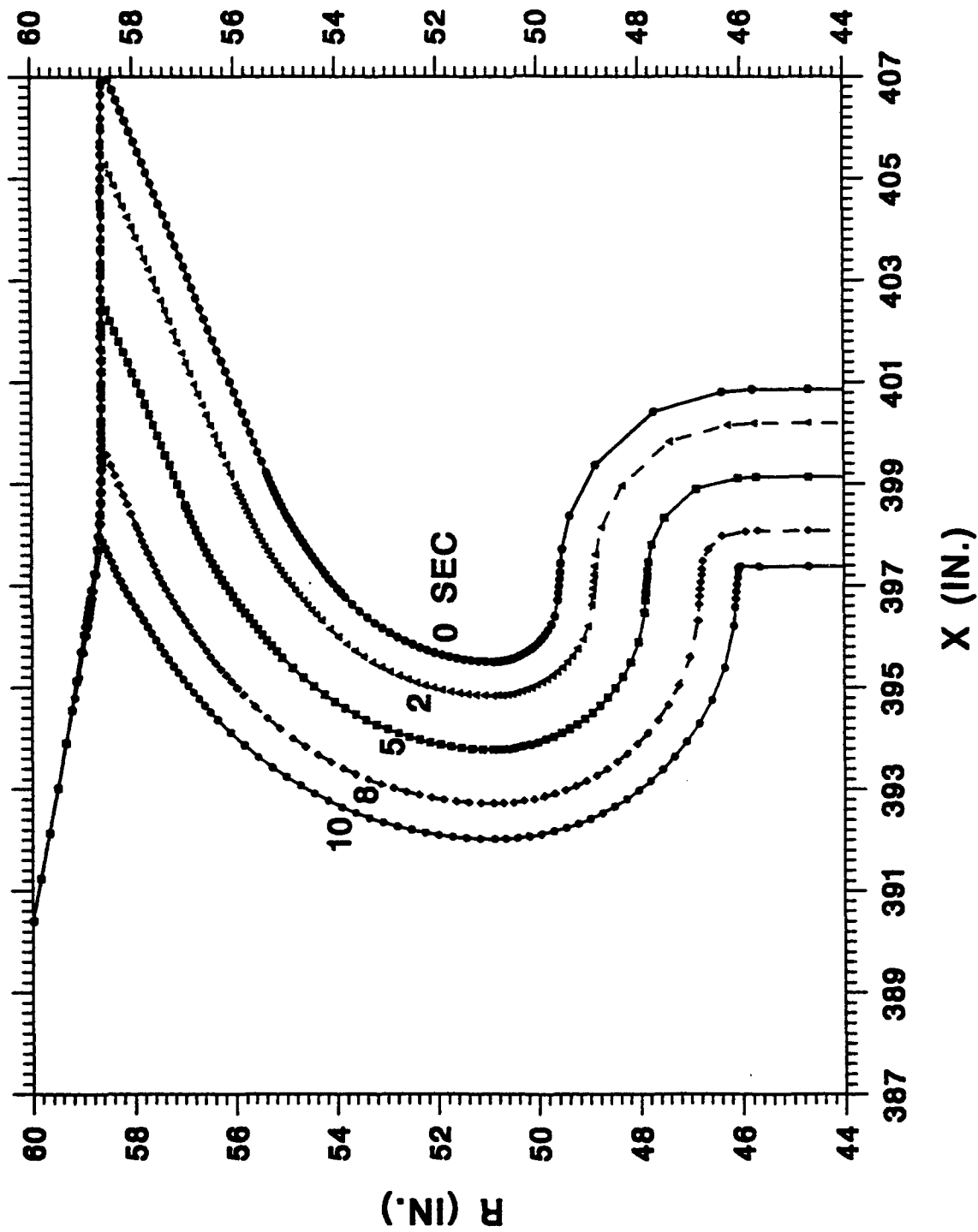


Figure 5. "Burn-Forward" from 10 sec (configurations at 0, 2, 5, 8, and 10 sec)

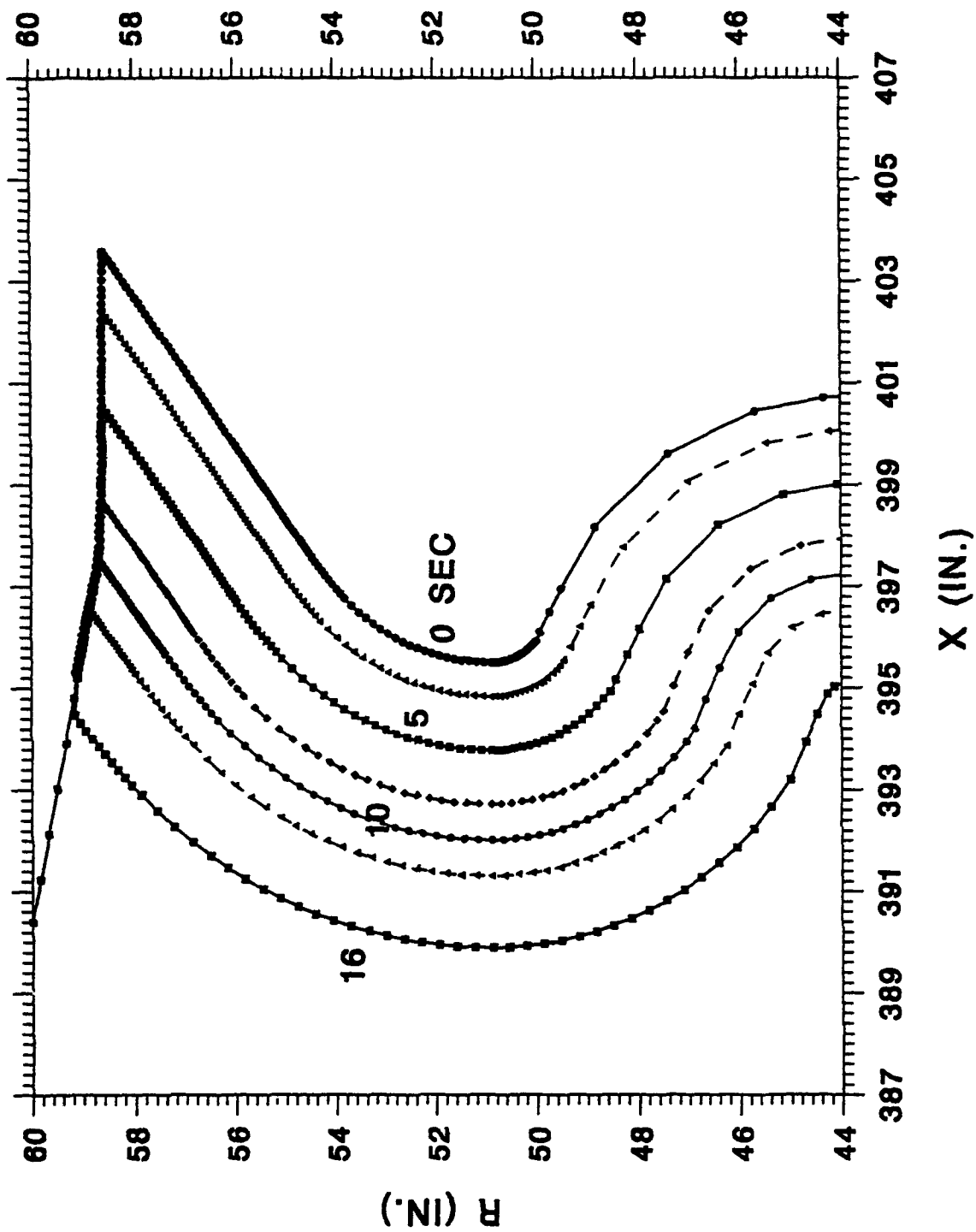


Figure 6. "Burn-Forward" from 16 sec (configurations at 0, 2, 5, 8, 10, 12, and 16 sec)

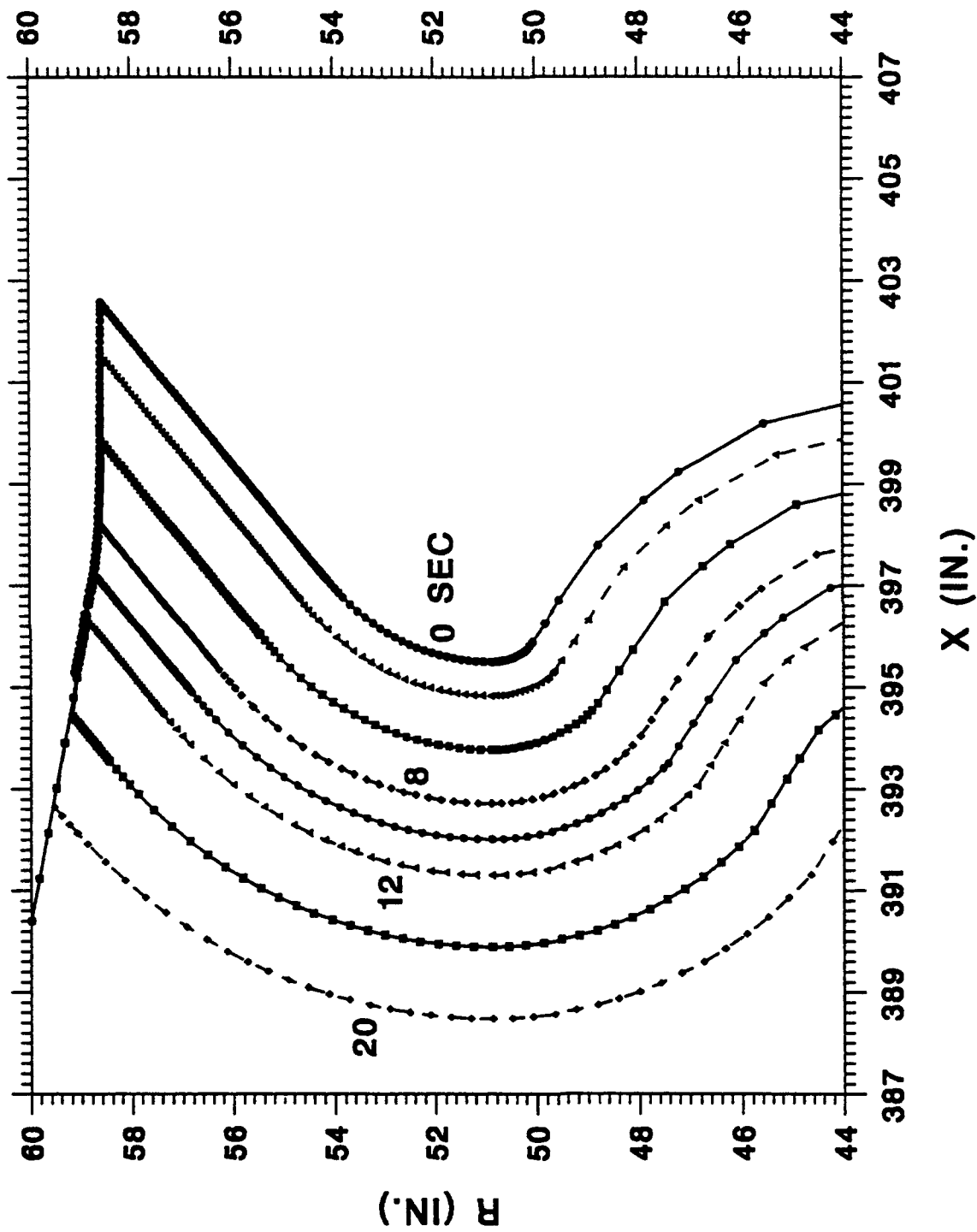


Figure 7. "Burn-Forward" from 20 sec (configurations at 0, 2, 5, 8, 10, 12, 16, and 20 sec)

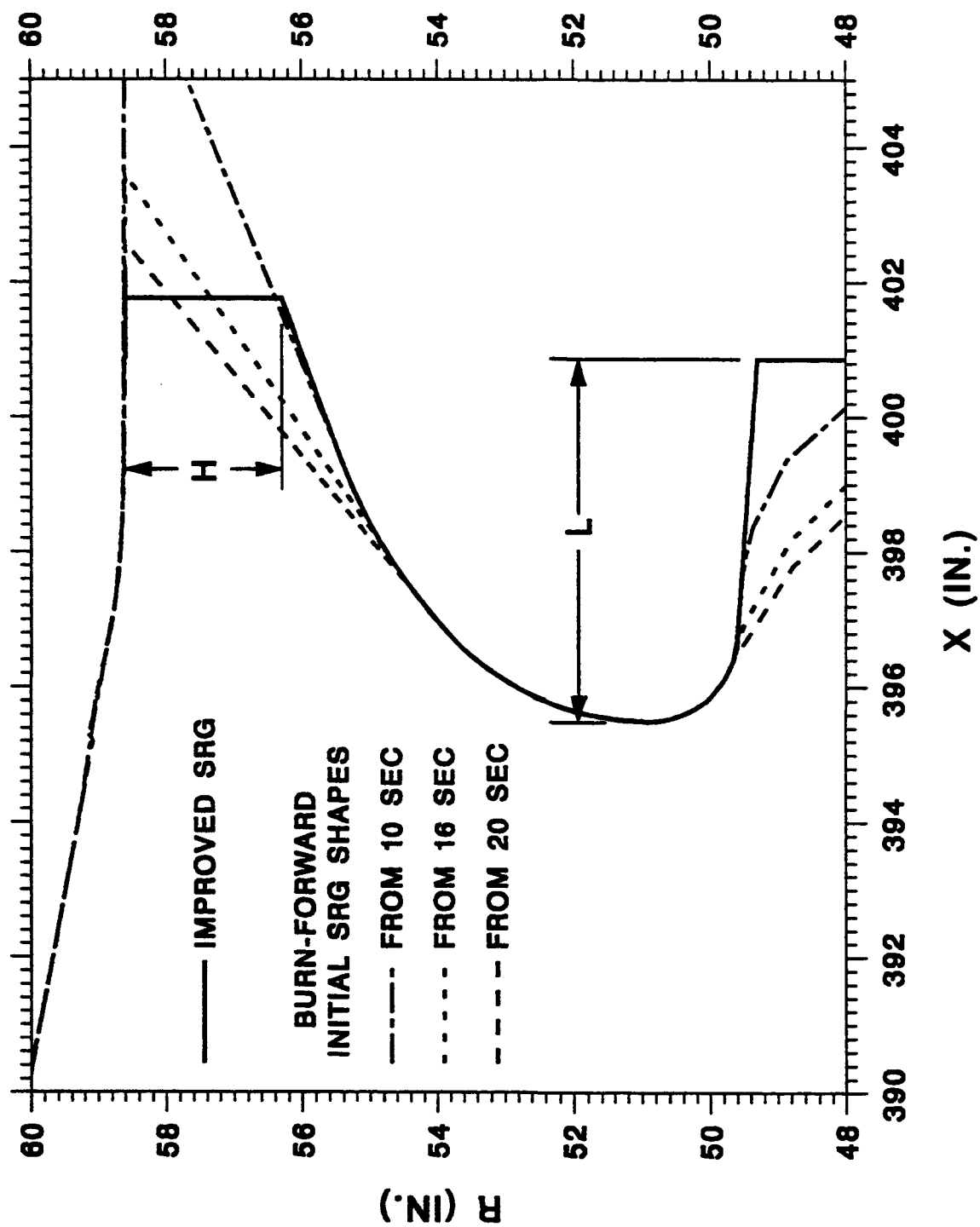


Figure 8. Initial SRG Shapes from "Burn-Forward" Analysis

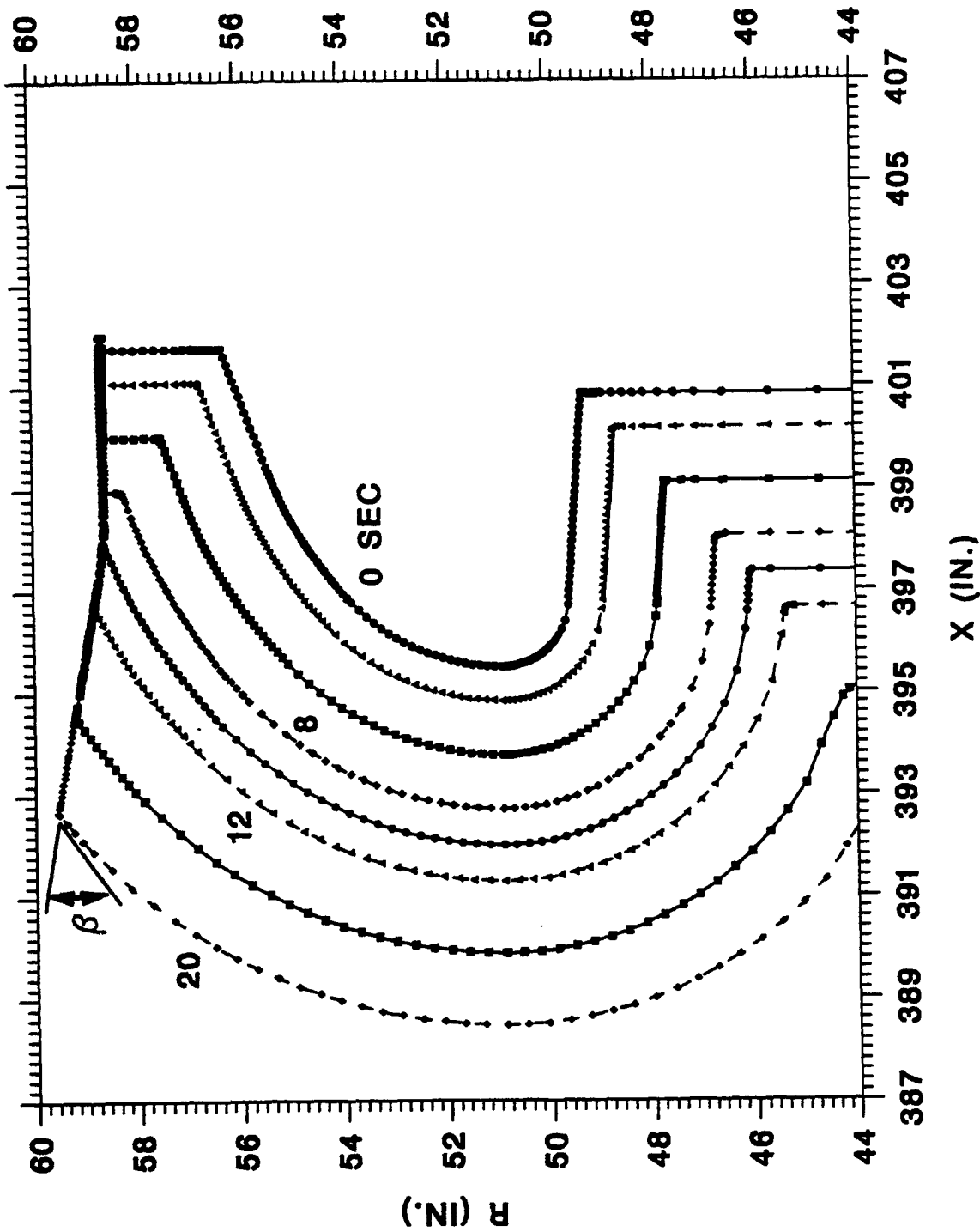


Figure 9. SRMU Improved Propellant SRG and Burn-Back
(configurations at 0, 2, 5, 8, 10, 12, 16, and 20 sec)

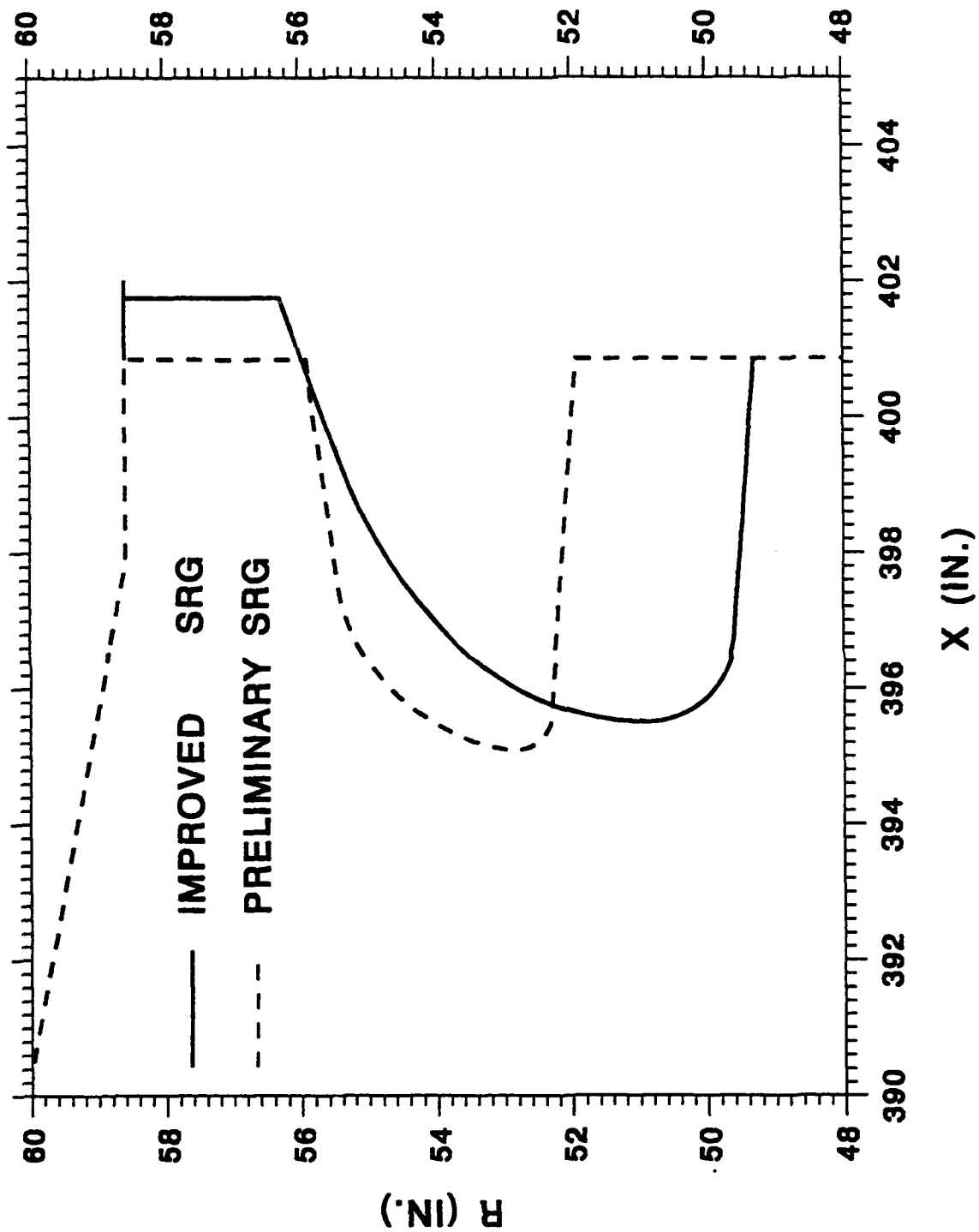


Figure 10. Comparison of Preliminary and Improved SRG

Table 1. Intersection Angle at Bondline

Time (sec)	Preliminary SRG β (°)	Improved SRG β (°)
10	25	24
12	37	35
16	47	44
20	55	45

The grain structural analysis using the ABAQUS (Ref. 6) finite-element program for the preliminary SRG and for the improved SRG has been carried out by the structural analysts. Figure 11 shows the combined results for the minimum margin of safety in the stress relief groove and at the bondline for the preliminary and for the improved SRGs under a high-temperature 32.22°C (90°F) firing condition. It is obvious that the improved SRG provides significant enhancement in the structural margin of safety over that of the preliminary SRG throughout motor firing. The additional margin of safety gained from the improved SRG is derived from a simple geometry modification in the stress relief groove design; but its effect on enhancing the integrity of the motor in the SRMU program is not trivial. The improved SRG design is more capable of accommodating variation in manufacturing processing and motor service life.

The method presented in this report is equally applicable to other motors with a stress relief groove in the grain of a different configuration from that of the SRMU. Since every motor has its own characteristics, the stress relief groove of a particular motor, in general, will be different from that of the SRMU. The motor characteristics, such as grain design, internal pressure distribution, propellant composition, motor case insulation profile, motor case bondline capability, and nozzle geometry, influence the design of a stress relief groove. Moreover, the method is not necessarily restricted to the stress relief groove analysis. It is believed that the "burn-forward" analysis method and the concept presented in this study can be extended to improve the entire grain design to achieve a predefined, unique ballistic feature for a solid rocket motor.

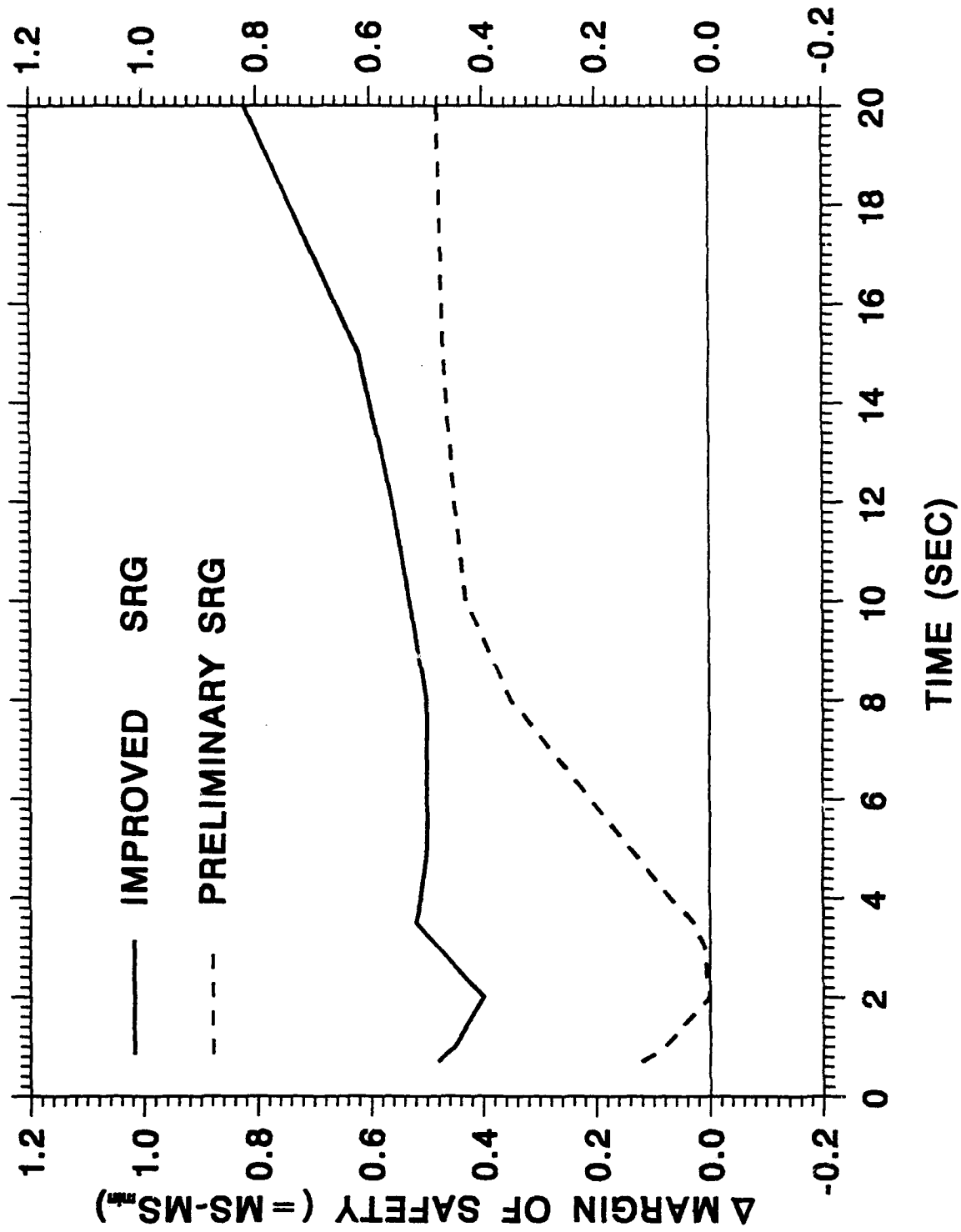


Figure 11. Margin of Safety Comparison (90°F)

4. CONCLUSIONS

A novel method to design a propellant stress relief groove for solid rocket motors has been presented. A unique feature of the method involves the use of the "burn-forward" analysis, which enables the desired bondline stress condition to be incorporated in the SRG design. For the Titan IV SRMU, the method presented in this study produces an improved SRG with a significantly enhanced structural margin of safety over that of the preliminary design throughout motor firing. This increases the confidence level of launching expensive payloads with the Titan IV SRMUs.

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